Fall 2013

Balancing Ecological and Economic Values in Northern Hardwood Stands: What Are the Trade-offs?

Daniel Woock Kilham
University of New Hampshire, Durham

Balancing Ecological and Economic Values in Northern Hardwood Stands: What Are the Trade-offs?

By

Daniel Woock Kilham
Bachelor of Science in Forestry (B.S.F.)
University of New Hampshire, 2011

Thesis

Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirements for the Degree of

Master of Science
in
Natural Resources: Forestry

September, 2013

This thesis has been examined and approved.

Thesis Director, Dr. Theodore E. Howard
Professor of Forestry Economics

Dr. Thomas D. Lee
Associate Professor of Forest Ecology

Dr. Mark J. Ducey
Professor of Forest Biometrics and Management

July 30, 2012

Date

Acknowledgements

I would like to express my gratitude to my committee chair, Professor Ted Howard, who tirelessly helped me through the entire process and for helping me start the project while I was an undergrad. I would also like to thank my committee members, Professors Tom Lee and Mark Ducey, for offering support and feedback, especially on the methodology. A thank you to Si Balch at the New England Forestry Foundation for his help with the data analysis and to my field technicians Katherine Sinacore and Eris Hargreaves for their help collecting data, carrying gear and not complaining about the bugs. A thanks also to Gabe Roxby for supplying the data logger that greatly increased the speed of data collection. Finally, I want to thank my friends and family for their support and encouragement.

Table of Contents

List of Tables

List of Figures

ABSTRACT

BALANCING ECOLOGICAL AND ECONOMIC VALUES IN NORTHERN HARDWOOD STANDS:

WHAT ARE THE TRADE-OFFS?

By

Daniel Woock Kilham

University of New Hampshire, September 2013

New England has 32 million acres of forested land, 27.5 million acres are private and 13.5 million of those private forests are family owned. Two of the main landowner objectives of privately owned forests in New England are generating income and promoting biodiversity and nature. Objectives were to develop a rapid ecological assessment method to aid management of private forests and to determine any trade-offs between economic and ecological values. We measured economic and ecological values in our study site in New Hampshire, and simulated four harvest treatments to determine the effects of different silvicultural approaches. Ecological values were measured from individual tree characteristics. Crown thinning harvests and regeneration shelterwood harvests improved biodiversity and average ecological value. Diameter limit harvests lowered the average economic and ecological score while ecologically-focused harvests had the opposite results. We concluded that there were few to no trade-offs between economic and ecological values.

Introduction

Forested land covers more than 32 million acres in the six states that make up New England: Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont (Forest Inventory Online Data, http://apps.fs.fed.us/fido/, accessed July 3rd, 2013). The majority of this forested land (17.5 million acres) is located in Maine, followed by New Hampshire (4.8 million acres) and Vermont (4.6 million acres). The most prevalent forest type in New England, covering 13.8 million acres, is a maple, beech and birch type. Spruce-fir, oak-hickory, and oak-pine forest types are also common.

Of the 32 million acres of forested land in New England, 86% (27.5 million acres) are private and 13.5 million of those private forests are held in family ownership (Butler, 2008). Butler and Leatherberry (2004) found that the most common reasons for landowners in New England to own land were the enjoyment of the beauty and the scenery, privacy and protection of nature and biological diversity. Twenty-seven percent of landowners reported harvesting in the past 5 years; however, only 9% of those surveyed indicated that timber harvesting was important to them. Possible explanations for these different percentages are that landowner objectives change over time and harvesting is necessary to accomplish non-timber objectives.

To accomplish objectives requiring timber harvesting, the most common silviculture techniques used in New England forests are variations on partial removal harvests. Single tree and group selection harvests are common in uneven-aged stands while shelterwood harvests are used in even-aged pine, oak, and pine-oak stands. Single tree and group selection cuts can be used for several different harvest prescriptions. A diameter limit harvest removes all the trees above a set diameter. Diameter limit harvests are often only beneficial for short-term financial gain and often leave the forest with an unhealthy mix of trees (Fajvan et al., 2002; Kenefic et al., 2005; Nyland, 2005). This prescription is sometimes referred to as "high grading" because of its tendency to remove only the valuable trees and leave a low quality stand. Single tree and group selection harvests can also be used as improvement operations, such as a crown thinning harvest, where large dominant and co-dominate trees are removed to allow growth in the canopy. Shelterwood harvests in the Northeast are often used in an even-aged management system to promote the growth of northern red oak (*Quercus rubra*) and eastern white pine (*Pinus strobus*) by providing partial shade for the seedlings and saplings (Loftis, 1990).

For the landowners who are harvesting, how does the harvesting of trees for financial reasons impact the ecological condition of their forest? How does the landowner objective to make money from the forest affect the objective to protect nature and biodiversity?

This study looks at the relationship between economic and ecological values on a tree by tree basis. Our objective is to create a quick method to evaluate any potential trade-offs between economic and ecological values from a harvest on an individual tree basis. This method could be used to train foresters to rapidly and easily assess a tree's values, both economic and ecological, to aid in their decision making.

The first part of this report reviews literature on evaluating ecological characteristics, starting with stand-level characteristics and moving to tree-based characteristics, and the determination of economic value of individual trees. The relationship between economic and ecological values on an individual tree basis will also be covered in this section. Next, we will discuss the methods used to collect and analyze data from our two hectare study site in Madbury, New Hampshire. This will be followed by an explanation of the case study harvests and their results. The subsequent section will cover a discussion about trade-offs between economic and ecological values when harvesting and the relationship between biodiversity and ecological values in our results. A concluding section discusses potential flaws and areas of improvement if the methods were to be replicated.

Literature Review

The literature review is presented in three parts The first part covers the current state of ecological evaluations for forested stands, the second part covers the economic evaluation for the northeast region of the United States, and the third part covers the development and analytic structure of the French marteloscope tool.

Ecological Evaluations:

Much of the research on ecological values of a forest has been done by collecting data on a stand-wide basis. Among the most popular ecological metrics is the Shannon-Wiener Index (SWI) which is commonly used to measure species diversity in a stand, although it can be used to measure diversity of other stand characteristics In general, the Shannon-Wiener Index characterizes diversity while accounting for both abundance and evenness of the species present. However, it does not capture species richness so a measure of total number of species is also useful.

Shannon-Wiener Index:

$$H = \sum p_i * \log_{10} (p_i)$$

Where H is the diversity index of species and p_i is the proportion of the total number of species made up by the *i*th species.

Shannon's Equitability, first developed by Pielou (1966) and also referred to as Pielou's J, is a Shannon-Wiener Index on a scale of 0 to 1 where 1 is complete evenness among species. Shannon's Equitability factors in the total number of species which is useful if species are lost or gained over time.

Shannon's Equitability:

$$E_H = H/\log10\ (S)$$

Where E_H is Shannon's Equitability, H is the diversity index of species and *S* is the total number of species in the community.

Species richness can be measured by recording the total number of species across stands or before and after a harvest.

Niese and Strong (1992) used SWI to measure tree species diversity before and after different harvests to determine if there were any trade-offs between economic values and biodiversity. They found that large group selection and crop tree harvests provided better economic returns and species diversity than diameter limit harvests. Shelterwood harvests were found to be the preferred treatment for promoting species diversity while small group selection was the best for promoting economic and diversity results. Lu and Buongiorno (1993) created a linear program to evaluate six cutting guides in terms of soil retention and ecological diversity. Their study defined ecological diversity as tree species diversity. They found that diameter limit harvests that only harvest merchantable species of a certain diameter and above reduced species diversity of the stand, while a diameter limit harvest that removed all trees of a certain diameter and above increased the species diversity of the stand. Schuler (2004) used SWI to measure tree species composition and biodiversity in managed forests over the past 50 years. He found diversity to be declining overall, regardless of harvesting technique. Welsh and Healy (1993) used SWI to measure avian species diversity in New Hampshire as it related to even-aged hardwood management. SWI can also be used to measure understory vegetation, amphibians, reptiles and insect species diversity, but it is not limited to measuring species diversity. Buongiorno et al. (2000) studied diameter distribution using SWI to determine relationships between tree size diversity and economic return. They found that it was possible to retain high tree size diversity without reducing present value of the income they would produce over an infinite time horizon using specific harvesting guides.

SWI is only one way to measure ecological value and often is the only index used in a study. Bullock et al. (2011) and Costanza et al. (2007)both studied how biodiversity and ecosystem services are related and found that biodiversity is not an accurate measure of ecosystem services or the ecological condition of a stand. Bullock et al. (2011) studied how the effectiveness of restoration projects on enhancing biodiversity and ecosystem services. Increasing biodiversity was not found to inevitably increase ecosystem services and vice versa. Costanza et al. (2007) studied the relationship between biodiversity and net primary production. They found that in colder climates, biodiversity negatively affects net primary production, while in warmer climates, biodiversity positively affects net primary production.

There are other types of ecological assessments that focus on multiple criteria. McElhinny et al. (2005) assessed literature on measuring forest and woodland structural complexity. They analyzed several indices used to evaluate a range of key structural elements. These elements include: foliage, canopy cover, tree diameter, tree height, tree spacing, stand biomass, tree species, understory vegetation, and deadwood. They also reviewed three different types of frameworks used to index these elements. The frameworks were either based on the cumulative score of elements or attributes, the average score of groups of elements or attributes, or the interactions of elements or attributes. McElhinny et al. (2005) concluded their report with suggestions on how to develop an effective index. First, the index should be based on a comprehensive set of attributes. This would require a larger set of attributes to be measured initially, though the authors note that the number of attributes can be reduced after correlations and relationships have been established. Second, the index should rely on a simple mathematical system. This allows the use of multiple attributes and can help visualize the results. Third, the scoring system should be relative to the type of stand being measured. This means that a stand with a naturally simple structure can still be ranked high and would not be compared to a naturally complex stand. For example, a forest with a simple canopy layer with a grassy understory would not be compared to one with a multiple layer canopy with shrubby understory. Stands with simple structure play an important role in the ecosystem and should not be measured with a scale designed only to promote complex stands. McElhinny et al. (2005) also note that a weighting system for the attributes can be applied but they have found very little guidance on a proper way to create a weighting system.

Whitman and Hagan (2007) analyzed numerous forest stand characteristics to determine if any were indicators that could be used to distinguish economically mature forest habitats from late successional forest habitats in the northeast United States. They selected variables that the literature suggested were indicators of late successional forests. Whitman and Hagan's aim was a simple, rapid index that was easy to measure, scientifically supported, and useful for foresters in decision making, similar to ideals suggested by McElhinny et al. (2005). They collected data on 46 variables in the categories of dead wood, epiphytes, ground flora, large wood, and trees. They applied a step-wise discriminant function analysis to the data to determine if any were indicators of late successional. Then they created a scoring system using the indicators selected by the step-wise regression. They found large ($\geq$ 40 cm dbh) alive and dead tree density to be to be the only statistically significant characteristic. They created two different indexes to distinguish late successional stands from economically mature stands. One index was for hardwood stands and the other was for spruce fir stands. The hardwood index only used the large alive and dead tree density characteristic while the spruce fir index also used a large log count, number of large living trees per acre. The hardwood index has a very simple field procedure. A forester in the field counts the number of alive or dead trees above 40 cm DBH per acre and then references a table that lists the number of live or dead trees a plot can have and the percentile chance of the plot being either, economically mature, late successional, or old growth (Table 1).

Table 1: Section of Whitman and Hagan's (2007) Northern Hardwood Successional Scoring Table

Large live and dead trees/plot*	NH-LSI Score	Seral Class Percentile		
		OG	LS	EM
0	0			3
1	1			7
2	2			14
3	3			21
4	3			28
5	4			34
6	4			45
7	5		3	62
8	5		8	79
9	6		21	86
10	6		26	93
11	7	4	28	93
12	7	12	46	97
13	7	20	46	97
14	8	24	51	97
15	8	28	59	100
16	8	32	72	
17	8	40	79	
18	9	48	90	
19	9	68	95	
20	9	68	97	
21	10	76	97	
22	10	80	97	
23	10	88	100	

Whitman and Hagan stressed that tree level indexes should be simple and easy to measure variables that required little training on the part of the forester, as to not add significantly to the time and cost collecting information about a stand. These indexes can be used to identify, inventory and monitor late successional forest with the goal of protecting and promoting late successional forests. The information gathered about late successional forests could be added to a database to act as steady state plots and aid in finding new late successional forests.

Franks and Reeves (1988) created a scoring system to calculate an approximate ecological value, in dollars, of urban trees. Their system set a dollar value per square inch of trunk for ecological value to determine the base ecological value of the tree. Then reduction factors are multiplied by the total value of the tree. There are three main categories of reduction factors. The first reduction category is local factors; these include any ecological characteristic that is constant or within immediate vicinity of the tree, such as wildlife use, water percolation, or soil erosion. The second reduction category is distant factors; these include characteristics that affect a larger area or even the whole ecosystem, such as nesting area for migratory birds, effects on downstream flooding, or siltation. The third reduction factor is the expected life of the tree. This is an estimation of how many more years the user thinks the tree will survive, from less than 5 years to over 30 years. The reduction factor for each category is the result the total number of characteristics observed for each category, where low scores would decrease the reduction factors, thereby reducing the total ecological value of the tree. For example, a healthy 24 inch DBH tree might have a cross section area of 452 square inches of solid wood inside it. Those 452 square inches are multiplied by the ecological value of $\$3/in^2$ of wood results in a base ecological value of $1356. However, the ecological score reductions for the tree are 0.7, 0.8, and 1.0, for local factors, distant factors and expected life, respectably. All three of the reductions are multiplied by the ecological value and the final value of the tree then becomes $759. Their system was heavily focused on trees in urban settings and noted that the using their system in rural and forested areas would require re-evaluating the methodology.

Economic Valuation:

For this study, we limited economic vale to only the value of commercial timber as expressed in terms of its stumpage value. Stumpage value represents the value of the products (lumber, pulpwood, firewood) that can be obtained from each tree minus the cost of harvest and transportation to the mill or factory. The value of each product varies depending on the quality or grade of the tree. Rast et al. (1973) provides a guide for grading hardwood log sections. This method assumes a log has four faces and the grade is based on the best face after eliminating the worst face. The presence of defects, such as rot or knots, reduces the quality of a face and will result in the log being given a lower grade (Table 2). There are several grades based on the quality of the log and each grade is listed in one of four groups. The first group is factory class lumber, wood generally used to make boards. Factory class lumber is usually broken down into three grades, 1, 2 and 3, where grade 1 logs are very high quality clear lumber and grade 3 logs have numerous knots and defects but can still be made into lumber (Table 2). The second group is construction class lumber, wood used for ties, pallets, timber or structural pieces. The third group is local-use class, firewood. There is also a group known as veneer class lumber, which is the highest value timber because of its lack of defects. Veneer lumber can be made from high quality factory class lumber. Any wood below those four grades is considered pulpwood.

Table 2: Hardwood Tree Grades for Factory Lumber (Hanks 1979)

Grade factor	Tree grade 1	Tree grade 2	Tree grade 3
Length of grading zone (feet)	Butt 16	Butt 16	Butt 16
Length of grading section* (feet)	Best 12	Best 12	Best 12
Dbh, minimum (inches)	16	13	10
Diameter, minimum inside bark at top of grading section (inches)	16	12	8
Cull deduction, including crook and sweep but excluding shake, maximum within grading section (percent)	9	40	50

Hanks (1976) created regression equations to estimate the board foot volumes by lumber grade in within a tree using the log grades established by Rast et al. (1973). These volumes can then be multiplied by the lumber prices to determine the lumber value of each tree. Manufacturing, transportation and logging costs are subtracted to yield the conversion return for a tree. Leak and Sendak (2002) and Sinacore (2013) employed this approach to determine the value of individual trees in northern hardwood forests in their analyses of grade and value change over time.

Buongiorno et al. (1994) created an economic cutting cycle for a steady state stand. They found the optimum cutting cycle by figuring out how long it would take the soil expectation value to return peak levels for the forest type. They used SWI to measure diameter distribution and used that as an indicator of stand structure and a determinant of biodiversity. They were able to find optimum cutting cycles to promote biodiversity without decreasing forest value. Lu and Buongiorno (1993) studies on the effects of different harvest types on economic values found that the economic harvesting guide they created could maintain revenue for the landowner while still retaining biodiversity. They calculated that a diameter limit harvest that removed all trees above 41 cm DBH every 15 years would lead to 95% retention of biodiversity and a soil rent that was about 70% of the maximum achievable. They also found that a high-grading harvest of all merchantable trees above 13 cm DBH had the lowest diversity among their tests and led to a negative soil rent.

Marteloscope Analysis:

Bruciamacchie (2005) created a field-based marteloscope system for training foresters and educating landowners and the public about the implications of uneven-aged silviculture treatments. The name is derived from the French words for timber marking, martleage, and the hammer employed in timber marking, martel. Recently, the uses of marteloscopes have expanded to include comparing the economic and ecological trade-offs of single tree removal. There are nearly 200 marteloscopes across France and several more in Belgium, Switzerland, and the United Kingdom. Each marteloscope in the system consists of carefully measured real forest stand and the analytic software needed to evaluate initial conditions and the impacts of simulated harvests. The typical physical marteloscope covers one hectare on which a 100% inventory of traditional forest measurements (diameter at breast height, total tree height, merchantable value, etc.) has been recorded. The azimuths and distances from grid points of all trees with a diameter at breast height of 7.5 cm or higher are measured to provide the basis of a stem map in the analytic model.

At some but not all of these marteloscope sites, ecological characteristics are recorded for each tree. These ecological characteristics are based on the presence of decay in the tree (broken branches, seams, presence of fungi or rot, etc.). Wildlife experts and ecologists from four fields (avian, insect, chiropteran, and mammalian ecology) were consulted to assign potential ecological scores to each ecological characteristic collected. These scores ranged from zero to four, with zero being not important to the animal and four being very important. For each tree, the highest of the four ecological scores was selected and used as the ecological score for that characteristic. For example, a dead branch would score a zero for mammals and bats, a one for birds and a four for insects which would result in a score of four for the tree.

Economic values for each tree are calculated by generating the total volume for the tree and multiplying that volume by a price per unit based on the species and grade of the tree and the diameter at breast height. Their grading system classified trees as either A, B, C, or D, which are very similar to Rast et al. (1973)'s log grades 1, 2, 3, and 4.

Table 3: Marteloscope Reasons for Removal of Tree

Reason for Removal
1. Stand Improvement
2. Regeneration
3. Cleaning
4. Harvest
5. Aesthetics
6. Diversity
7. Exploitation

The system allows users to select trees within the study site to be theoretically harvested. The users move through the physical forest and select the trees based on their knowledge of forestry and a given management objective. The users record which trees to remove and the reason why the tree should be removed. The software model takes the users' selections and generates the results and analysis of a theoretical harvest. These results include per hectare basal areas and volumes before and after the harvest, diameter distributions, species composition graphs and changes in average economic and ecological values. These results can be compared with other theoretical harvests to analyze the trade-offs among different objectives. This helps foresters understand the trade-offs between the economic and ecological value of the tree. The marteloscope methodology was the basis for our study.

The Department of Natural Resources of Quebec has installed several permanent plots across the province called martelodromes (http://www.mrn.gouv.qc.ca/forets/entreprises/entreprises-martelage-exercice.jsp). The trees in the martelodromes are evaluated for their ecological characteristics and are used as a training tool for identifying and classifying risk factors in trees. Risk factors included physical defects such as seams, broken branches, and cavities, along with evidence of insects and disease. These martelodromes are used to train timber markers in assessing risk of mortality of a tree during the next cutting cycle. Quebec has a province regulation that requires foresters to remove dead and decaying trees in an attempt to improve the overall quality of timber throughout the province. Guillemette et al. (2008) created a mortality ranking system for uneven-aged northern hardwood stands. Their system was based on the presence of major crown and bole defects. They found that trees with potential sawtimber had a lower chance of mortality than trees with no merchantability. However, they were only focusing on three species of trees. Fortin et al. (2008) also found that trees with potential sawtimber had higher chances of survival than those without. Our mortality risk assessment originated from their work and was later simplified.

Soucy et al. (2013) at the University of Moncton at Edmondston, New Brunswick, have established four marteloscopes in central New Brunswick. The New England Forestry

Foundation is also currently developing their own marteloscope for training purposes in New England.

In examining several French marteloscopes, Bruiciamacchie (personal communication, November 2012) found a relationship between the ecological and economic values of trees. Trees with high economic value tended to have low ecological value and trees with high ecological value had low economic value. Occasionally trees with high economic value had high ecological value but this was not common because, in the French forest management context, a high ecological score indicates the presence of decay which lowers the economic value of the tree.

We wanted to see if the ecological and economic values of trees in a northern hardwood forest would have a similar relationship as in the French case. To do this we needed to determine important ecological criteria for the region. Preserving wildlife and biodiversity were important factors for many landowners in New England (Butler and Leatherberry, 2004). To survive and reproduce, wildlife need food, water, shelter and spatial distribution (Schemnitz, 1980). Individual trees in a forest cannot significantly affect water availability or spatial distribution for a species but can provide a source of food and shelter. DeGraaf and Healy (1992) and DeGraaf and Yamasaki (2001) emphasize the importance of cavity trees and trees with large branching patterns as sources of cover for many

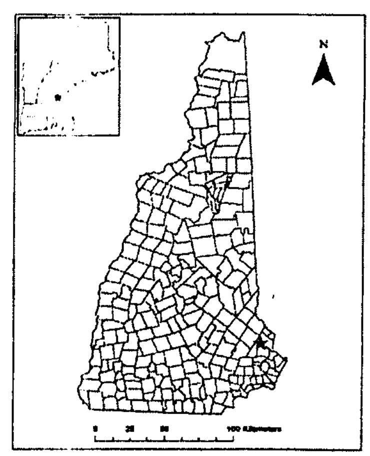

Figure 1: Location of Kingman Farm within the state of New Hampshire and the northeastern United States

New England forest wildlife species. Eastern hemlock (*Tsuga canadensis*) provides wintering habitat for deer (Reay, 2000). Martin et al. (1961) noted that hard mast, such as acorns, are commonly eaten by a wide variety of wildlife species. Dead and decaying branches and logs provide food and shelter for insects, insects that are a food source for other species (DeGraaf and Healy, 1992).

This study addresses the relationship between economic and ecological values on an individual tree basis. The objective is to determine if individual tree-based data can be used to help landowners make harvesting decisions.

Methods:

Site Selection and Plot Establishment:

The study site is located in the forested area of the University of New Hampshire's Kingman Farm in Madbury, NH (Figure 1, Figure 2). Kingman Farm has a total of 334 acres of which 234 are forested. The university acquired the land in 1961 and has been managing the land for teaching, research and recreation with minimal harvesting. Numerous stone walls and remnants of barbwire indicate the forest had been cleared for farmland through the 19th century.

The site is dominated by northern red oak (*Quercus rubra*), eastern hemlock (*Tsuga canadensis*), and American beech (*Fagus grandifolia*). Red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), black birch (*Betula nigra*), and grey birch (*Betula populifolia*) are also common. The site has an average slope of 5 degrees, generally facing east. The soil type for the site is a Charlton very stony fine sandy loam, 3 to 8 percent slopes (USGS Web Soil Survey). A small seasonal stream runs through the site from the northwestern corner towards the center then towards the northeastern corner.

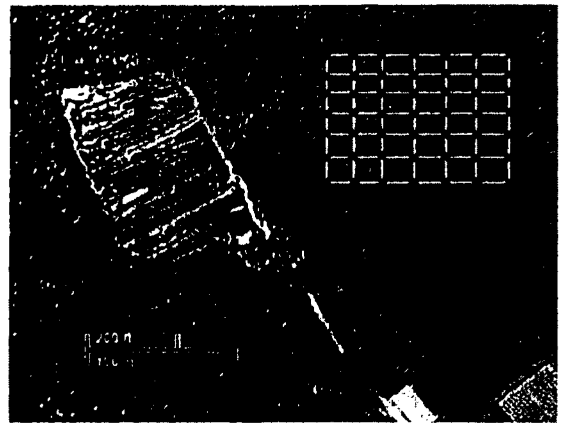

Figure 2: Study Site at Kingman Farm, Madbury, NH. Dots represent pins and lines represent study area. Cleared area on left is university's composting operation.

The two hectare (~5 acres) study site was established in the spring of 2011. Following the methods of Bruciamacchie et al. (2005) a grid of 20 (66ft) meters by 20 meters was established by setting a center pin and working clockwise using a staff compass and measuring tape. The grid cells are aligned to magnetic cardinal directions (Figure 3). Labeled wire pins were placed at each intersection to aid with later data collection.

This site was selected for several reasons. First, the site is easily accessible for subsequent instructional and research uses. Second, this site has minimal interference with other uses of the property. The Kingman Farm is currently under a management plan that allows for harvesting for research, recreation or timber improvement purposes. The site is small enough and straddles two forest types which will reduce the chances of a harvesting operation occurring throughout the entire site. Third, because the site is located on two forest types, it increases the tree species diversity. The western section is predominately an early to mid-successional mixed hardwood stand while the eastern section is mainly a mature red oak stand. Fourth, the mature red oak area allows for a realistic theoretical harvest because mature red oak stands are common in northern New England and frequently harvested.

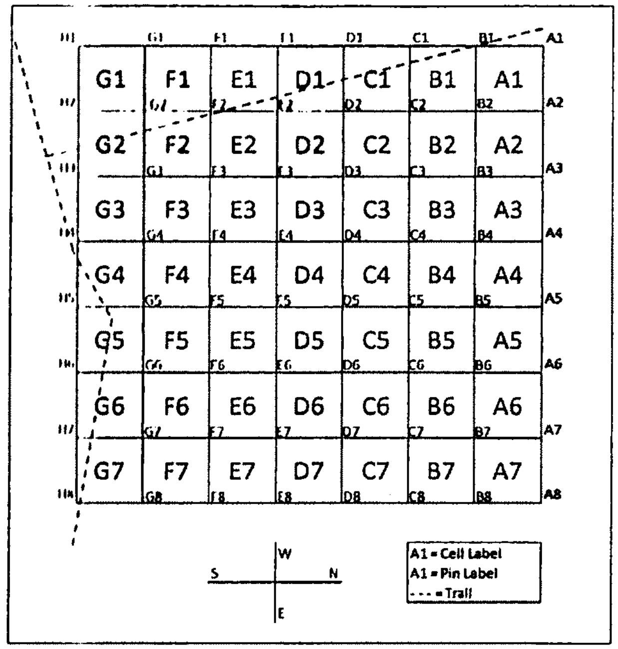

Figure 3: Grid Layout of Study Site at Kingman Farm, Madbury, NH

Data Collection:

Data were collected during June and July of 2012. Starting at the center pin and working clockwise, all trees above 3.5 inch diameter at breast height (DBH) were recorded by species and marked with a numbered aluminum tag. DBH of the tree was recorded to the nearest 0.1 inch using a research grade DBH tape. The total height of the tree was recorded to the nearest 5 foot increment. Total merchantable height was recorded in half-log (8ft) increments for all trees with a DBH of 6 inches or greater because that diameter is the minimum for merchantability in the region. Total merchantable height is the total number of log (16 foot) sections of the tree that are greater than 4 inch diameter that could be used for either sawlogs or pulpwood.

For a hardwood log to contain sawtimber, a log must have at least a ½ 16-foot log of sawtimber quality material, with a 6" minimum top, and have a minimum dbh of 10.0 inches. If a hardwood log had a DBH of less than 10.0 inches it was classified as pulpwood. For a softwood log to contain sawtimber, a log must have at least a ½ 16-foot log of sawtimber quality material, with a 6" minimum top, and have a minimum dbh of 8.5 inches. If a softwood log has a DBH of less than 8.5 inches it was classified as pulpwood. Sawlog height is the total number of 16 foot sections that could be used for sawlogs.

Every tree that contained sawtimber had the first 16 feet from the base evaluated for quality. This measurement is called the 1st log grade. Grading of the 1st log was based on the guide created by Rast et al. (1973). The four faces of the log were inspected for defects, knots, decay or curving. If the log is very clear with few to no defects the log is graded as Grade 1. If the log has some defects but at least 50% of the wood was defect free it was given a Grade 2. If less than half of the log was clear but still straight enough to be used for lumber it was given a Grade 3. Logs that were deemed unusable for lumber were classified as pulpwood.

The canopy position of each tree relative to the stand was recorded as either dominant, co-dominant, intermediate, or suppressed. Dominant trees have crowns that extend above the general level of the crown cover and are receiving full light from above and partly from the side. Co-dominant trees have crowns that form the general level of the crown cover and are receiving full light from above but comparatively little from the sides. Intermediate trees are shorter than those in the preceding classes but with crowns extending into the crown cover formed by the co-dominant and dominant trees; receiving a little direct light from above but none from the sides. Suppressed trees are entirely below the general level of the crown cover, receiving little to no direct sunlight either from above or the sides (Smith et al., 1997).

An estimation of each tree's crown shape and size was recorded based on a simple scale from observations under the tree. A tree's crown shape and size is relative to the surrounding trees and also to the general shape of the crown itself. While the shape and size of the tree's crown can be affected by the position in the crown's position in the canopy, canopy position is not the sole determining factor for the crown shape and size measurement. For example, a dominant tree could have a small, narrow crown even though it is above the canopy, while an intermediate tree could have a large expanding crown. A full, expansive crown with many branches extending outward that was not being encroached by another tree was given a 1, a crown that was only slightly crowded by another tree was given a 2, a crown that was almost completely crowded by other trees was given a 3, and a small, narrow crown that was under another crown or just breaking through the canopy was given a 4.

The height of lowest branch of the live canopy of the tree was recorded in feet using a laser rangefinder. This was used to estimate height of crown.

Each tree recorded was assigned a risk of mortality rating based on observed signs of mortality and an estimate of the tree's chance of death in the next 10 years. A tree's chance of death was influenced by its crown class, shade tolerance, and the life expectancy of the tree species. A tree with no structural defects and a low chance of death in the next 10 years was given a mortality risk score of 0. A tree with some dead branches, few conks or mushrooms on branches, few cavities and a chance of death in the next 5 to 10 years was given a score of 1. A tree with numerous dead branches, visible signs of rot, conks on trunk, and a high chance of death in the next 10 years was given a score of 2. A tree that is already dead or very close to death was given a score of 3.

The distance and azimuth of the tree from a labeled wire pin was recorded using TruPulse 360B laser rangefinder. These data is used to map the trees in a computer program to aid in the analysis and for other studies.

Data Analysis:

Data were analyzed using a Microsoft Excel program modified from the original developed by Bruciamacchie (personal communication, 2012). Bruciamacchie's original model was used to analyze the economic and ecological trade-offs of prescriptions applied to marteloscopes. The program needed to be adapted from a European based system to a New England based system. These adaptations included translating French text to English, converting from metric to English units, replacing existing volume equations with equations used in New England, and modifying the ecological scoring system to correspond with New England landowner objectives and management approaches. This modified program analyzes raw data collected from the field and generates economic and ecological values. The program can also run simulation harvests where a user selects trees to harvest and the program analyzes the results of those choices. The model provides information about the stand before and after the harvest along with data regarding what was removed. The information produced includes diameter distributions, log grade distributions, average economic and ecological values, Shannon-Wiener Indices, and species compositions. The model also creates a stem map of all the trees in the study site. This stem map can be updated after a simulated harvest has been completed to show which trees were removed and which trees were left.

Bruciamacchie's analysis only focused on a single maximal ecological score while ours integrates four different scores. By having more than one score, our system is able to use a simple mathematic equation to reach a total ecological score for the tree, as suggested by McElhinny et al. (2005). Bruciamacchie's ecological scoring system focused on the physical condition of the tree and the severity of the tree's decomposition. The ecological influence these trees had on wildlife was derived by consulting wildlife experts after the data were collected. Our study employed the opposite approach, where wildlife factors were considered first and then ecological indicators, hardmast production, shelter, decomposition, and commonality, were assessed.

For the analysis, the study site was reduced to a one hectare plot. The one hectare plot was the eastern half of the study site which is a mature red oak stand. This allowed us to focus on managing a single stand type instead of two forest types. The western half of the study site is a regenerating mixed hardwood stand which is not ready for treatment because the average diameters were too small to produce sufficient sawtimber to cover the cost of the harvest.

Only trees above 6 inches DBH were included in the analysis. Trees less than 6 inches DBH are not usually recorded in timber harvests and would skew results. Reducing the size of the study area and increasing the minimum DBH reduced the data set allowing for a more practical analysis. Total ecological and economic values were calculated for each tree.

Ecological Scores:

Following the recommendations of McElhinny et al. (2005), we designed a simple scoring system to evaluate the ecological value of each tree. Each tree was assigned an ecological score, from 0 to 3, in four different categories and then those scores were combined into a total ecological score for the tree. A tree's ecological score could range from a minimum of 0 to a maximum of 12. Actual ecological scores ranged from 0 to 9.

Hard Mast:

Trees were rated on a scale of 0-3 for their ability to produce hard mast. Species that could not produce hard mast or were too small to produce acorns were given a score of 0. Rose et al. (2012) found that increases in diameter at breast height were linked to increases in overall acorn production in oaks, therefor, the larger the oak tree the higher the ecological score. Red oaks and beech trees above 12 inches DBH but below 18 inches DBH were given scores of 1. Red oaks and beech trees above 18 inches DBH but below 24 inches DBH were given scores of 2 and a red oak or beech above 24 inches DBH received a score of 3. These scores were calculated during the analysis stage of the model. It should be noted that soft mast producing trees could be included in this category but there were none in the study site.

Wildlife Trees:

Each tree was scored based on its potential to provide shelter and reproduction sites for wildlife. The canopy size values were used to calculate the wildlife potential. A tree with a full canopy has more branches expanding outward thus creating more favorable branch configurations for nests (DeGraaf and Healy, 1992; DeGraaf and Yamasaki, 2001). Trees with large full canopies received scores of 3 or 2 while trees with small thin canopies received scores of 1 or 0. Trees with large cavities also received higher scores for the potential habitat of cavity nesting animals. Hemlocks received scores of 2 because of their potential for deer wintering areas (Reay, 2000).

Mortality Risk:

The mortality risk score for each tree is the score assigned from the observed signs of decay combined with any factors increasing the chance of death in the next 10 years. This was assessed in the field following the framework previously described. Those factors include species, crown position, and shade tolerance. For example, a suppressed shade-intolerant species or a species susceptible to wind-throw would have a higher mortality risk score even without signs of decay.

Species Rarity:

The ecological score for species rarity is a comparison of the tree's species compared to the total number of species in the stand. This measurement is only focused on the trees within this stand and does not consider trees in the surrounding area or trees that are rare to the region. It is also the individual species portion of the Shannon-Wiener Index that is used to compute the Shannon-Wiener Index. A score from 0-3 is assigned based on how common the species, with 0 being very common species (>30% of total species) in the site, 1 being uncommon (30%-10%), 2 being rare (10%-1%), and 3 being extremely rare (<1%). This ranking is based only on the species present in the stand before and after a harvest. If a stand was dominated by red oak trees each red oak would receive a score of 0 but if a harvest operation removed all but one of the red oaks, that red oak's rarity score would be a 3. The rarity of a specific species on a larger scale such as region or landscape is not considered in this ecological score.

Economic Value:

The economic value of each tree is defined as its stumpage value and is calculated as a function of the volumes and prices of the sawtimber and pulpwood products contained the tree.

The pulpwood volume of each tree was calculated in cubic feet using Honer's total volume equation (Honer, 1967).

$$V_{Tot} = \frac{D^2}{b_0 + \frac{b_1}{H}}$$

Where V_{Tot} = Total volume in ft^3, D = diameter outside bark (inches) measured at breast height (4.5 ft), H = total height (ft), b_0 and b_1 are species specific regression coefficients (Appendix B). The cubic volume of the tree was then converted to tons using conversion factors supplied by New England Forestry Foundation (Si Balch, personal communication, January 23rd 2013).

If the tree had any sawtimber, the volume was calculated in board feet using Wiant Jr and Castaneda (1977) volume equation.

$$\text{VOLUME} = [(a_0+a_1H+a_2H^2) + (b_0+b_1H+b_2H^2)D + (C_0+c_1H+C_2H^2)D^2]\,[(FC-78)\,(.03)+1]$$

Where D = diameter at breast height

H = merchantable height to a 10" top in 16 foot logs

FC = Girard form class

a_0 =	-13.3521
a_1 =	9.58615
a_2 =	1.52968
b_0 =	1.7962
b_1 =	-2.59995
b_2 =	-0.27465
c_0 =	0.04482
c_1 =	0.45997
c_2 =	-0.00961

Each tree's sawlog (board feet) and pulpwood (tons) volume was calculated and multiplied by the species stumpage price for each product. Stumpage reports came from New England Forestry Foundation (Si Balch, personal communication, March 19th 2013). The 1st log grade value for each tree was used as a modifier for the sawlog values. A 1st log grade score of 1 increased the total sawlog value of the tree by 20% while a 1st log grade score of 3 decreased the sawlog value by 20%. A score of 2 was deemed average and the sawlog value was not adjusted. We had insufficient market information to accurately price all three grades of sawtimber so we simplified the Hanks' (1976) method by setting the price of grade 2 logs at average stumpage price and increasing and lowering that price by 20% for grade 1 and grade 3 logs, respectively. The sawlog value and pulpwood value were combined for the total economic value of the tree. For example, a 16.7 inch DBH red oak with 1 16-foot logs of pulpwood and 3 logs of grade 1 sawtimber would have a pulpwood value of $2.89 and a sawtimber value of $93.91 (base value $78.26 + 20% for grade 1 lumber) for a total value of $96.79.

Case Study Harvests:

Four theoretical harvests were designed to test the ecological and economic impacts of different silviculture prescriptions. The harvests were evaluated on their effectiveness at increasing favorable metrics, such as average ecological value or Shannon-Wiener Index, while also promoting future value in the stand. The four prescriptions are described below. The markings for the first two prescriptions were accomplished in the field, evaluating individual trees. The latter two prescriptions were implemented by applying removal criteria to existing tree data.

Crown Thinning:

In a crown thinning, trees are removed from the upper crown classes to open up the canopy and favor the development of the most promising trees of the same canopy class. This is a common improvement harvest for mature uneven-aged stands. Most of the trees designated in the field for removal are co-dominant but intermediate trees that could interfere with the development of potential crop trees are also designated (Smith et al., 1997). Our goal for this prescription was to promote future growth of valuable trees and retain average economic values; ecological values were not explicitly considered. We expected that the attempt to improve the economic value of the stand will not affect the ecological score because the number of trees being removed is low and because the trees being removed will be mainly red oak which is the dominant species, thereby not negatively affecting species diversity.

Shelterwood:

This was a seed cutting harvest of a two stage shelterwood harvest which aimed to remove 40% of the basal area to open enough vacant growing space to allow the establishment of regeneration. The trees designated in the field for removal in this cutting were low quality for both seed production and future value (Smith et al., 1997). Red oaks were favored for retention because of their potential future value as high demand lumber. In roughly 10 years, a removal cutting would follow this seed harvest but because we are limited to current values we do not predict the outcome of a removal cutting. Our expectation for this harvest was that the average economic value will go down slightly but the average ecological score will rise. We expect the average economic value to be lower after the harvest because the majority of the trees being removed are large, valuable trees; however, the removal of those trees will improve the species diversity by removing the most dominant species thereby evening out the species diversity of the stand.

Diameter Limit:

Diameter limit cutting is when only merchantable trees above a stand- or species-specific size threshold are cut (Kenefic et al., 2005). The minimum diameter for this harvest was set at 16 inches, so any tree with a DBH of 16 inches or higher was removed. Ecological and economic values were not explicitly considered in the trees that were removed. Our expectation for this harvest was that the short-term economic objective would going greatly reduce the post-harvest average economic and ecological value for the stand as suggested by the literature.

Ecological:

This prescription removed any tree that had an ecological score of 3 or less. The purpose of this prescription was to increase the average ecological score per tree by removing the lowest scoring trees. Butler and Leatherberry (2004) found that family landowners in the northeast region had forest health and biodiversity as a main focus for their forests. This harvest is an attempt to replicate a landowner promoting biodiversity and stand health by removing trees of low ecological value as defined by our scoring system. Our expectation for this harvest was that it will improve the average ecological value and biodiversity of the stand. We also expect that the increase in ecological score will lower the average economic value because we do not suspect that trees with high ecological scores will also have high economic values (Bruiciamacchie, personal communication, November 2012).

The trees that would be marked for removal in each prescription were noted as such in the analytic model. For each prescription, basal area, average DBH, average ecological score, average economic value, and cubic feet per hectare were generated for harvested and remaining trees. The post-harvest results included an updated rarity value for the remaining trees because the species richness changes when trees are removed. A Shannon-Wiener Index was calculated to evaluate species diversity across the site (Shannon, 1948). Shannon's Equitability was also calculated to evaluate the species because it incorporates the number of species in the stand which might change after a harvest. These last two calculations allow for a comparison between an established biodiversity indicator (Shannon-Wiener Index) and our new ecological scoring system.

Evaluation Criteria

Each harvest will be evaluated on how well it met expectations, any changes in economic, ecological and biodiversity values, and the relationship between economic and ecological scores.

Results:

Initial:

The site had 387 trees above 6in DBH, with an average DBH of 12.1 inches. The basal area of the site was 143.3 ft^2/acre and the total volume was 4490 ft^3/acre. The average volume per tree was 29.39 ft^3. The average ecological score per tree was 3.45 out of 12 (the highest score a tree received was 9) and the average economic value was $32.65. The base Shannon-Wiener Index was 1.67 and the Shannon's Equitability was 0.65. The site had 12 species of trees; the most abundant species were red oak (52%) and red maple (13%).

Crown Thinning:

The crown thinning prescription removed 56 trees with an average DBH of 15.4 inches. The basal area of the removed trees was 30.8 ft^2/acre and the total volume was 1045 ft^3/acre. The average volume per tree removed was 46.12 ft^3. The average ecological score of the trees removed was 3.68 and the average economic value was $60.23. The total value of the trees removed was $3,373.

The remaining 331 trees had an average DBH of 11.6 inches. The basal area of the site was 112.5 ft^2/acre and the total volume was 3445 ft^3/acre. The average volume per tree was 26.6 ft^3. The average ecological score per tree was 3.31 out of 9 and the average economic value was $27.99. The Shannon-Wiener Index was 1.80 and the Shannon's Equitability was 0.70. After the harvest, the most abundant species were red oak (45%), red maple (16%) and hemlock (11%).

Shelterwood:

The shelterwood prescription removed 139 trees with an average DBH of 13.1 inches. The basal area of the removed trees was 57.0 ft^2/acre and the total volume was 1842 ft^3/acre. The average volume per tree removed was 32.95 ft^3. The average ecological score of the trees removed was 3.37 and the average economic value was $38.58. The total value of the trees removed was $5,362.

The remaining 248 trees had an average DBH of 11.6 inches. The basal area of the site was 86.3 ft^2/acre and the total volume was 2649 ft^3/acre. The average volume per tree was 27.4 ft^3. The average ecological score per tree was 3.50 out of 9 and the average economic value was $29.33. The Shannon-Wiener Index was 1.92 and the Shannon's Equitability was 0.75. After the harvest, the most abundant species were red oak (41%), red maple (17%) and sugar maple (7%).

Diameter Limit:

The diameter limit prescription removed 100 trees with an average DBH of 18.2 inches. The basal area of the removed trees was 74.1 ft^2/acre and the total volume was 2536 ft^3/acre. The average volume per tree removed was 62.7 ft^3. The average ecological score of the trees removed was 4.80 and the average economic value was $89.95. The total value of the trees removed was $8,995.

The remaining 287 trees had an average DBH of 10.0 inches. The basal area of the site was 69.2 ft^2/acre and the total volume was 1954 ft^3/acre. The average volume per tree was 17.8 ft^3. The average ecological score per tree was 2.86 out of 9 and the average economic value was $12.69. The Shannon-Wiener Index was 1.96 and the Shannon's Equitability was 0.76. After the harvest, the most abundant species were red oak (37%), red maple (19%) and hemlock (12%).

Ecological:

The ecological prescription removed 200 trees with an average DBH of 10.2 inches. The basal area of the removed trees was 51.0 ft^2/acre and the total volume was 1503 ft^3/acre.

The average volume per tree removed was 19.5 ft^3. The average ecological score of the trees removed was 2.26 and the average economic value was $16.97. The total value of the trees removed was $3,394.

The remaining 187 trees had an average DBH of 14.2 inches. The basal area of the site was 92.3 ft^2/acre and the total volume was 2988 ft^3/acre. The average volume per tree was 39.9 ft^3. The average ecological score per tree was 4.53 out of 9 and the average economic value was $49.43. The Shannon-Wiener Index was 1.47 and the Shannon's Equitability was 0.57. After the harvest, the most abundant species were red oak (58%) and hemlock (19%).

Table 4: Comparison of Case Study Harvests

		Crown Thinning		Shelterwood		Diameter Limit		Ecological	
	Initial	Cut	After	Cut	After	Cut	After	Cut	After
Total Trees	387	56	331	139	248	100	287	200	187
Average DBH (in)	12.1	15.4	11.6	13.1	11.6	18.2	10.0	10.2	14.2
Basal Area ft^2/acre	143.3	30.8	112.5	57.0	86.3	74.1	69.2	51.0	92.3
Total Volume ft^3/acre	4490	1045	3445	1842	2649	2536	1954	1503	2988
Average Vol/Tree (ft^3)	29.39	46.12	26.6	32.95	27.4	62.7	17.8	19.5	39.9
Avg Ecological Score	3.45	3.68	3.31	3.37	3.50	4.80	2.86	2.26	4.53
Avg Economic Value	$32.65	$60.23	$27.99	$38.58	$29.33	$89.95	$12.69	$16.97	$49.43
Shannon-Wiener Index	1.67	-	1.80	-	1.92	-	1.96	-	1.47
Shannon's Equitability	0.65	-	0.70	-	0.75	-	0.76	-	0.57
Harvest Value	-	$3,373	-	$5,362	-	$8,995	-	$3,394	-
Remaining Value	$12,637	-	$9,264	-	$7,275	-	$3,642	-	$9,243

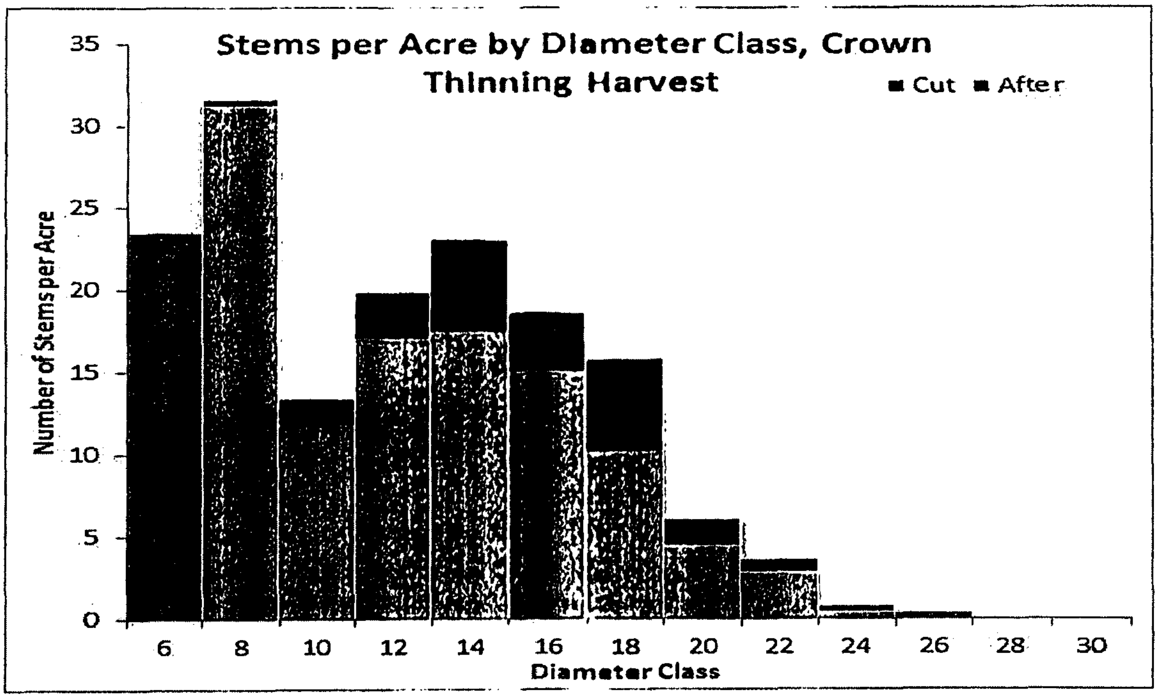

Figure 4. Stems per Acre by Diameter Class for Crown Thinning Harvest

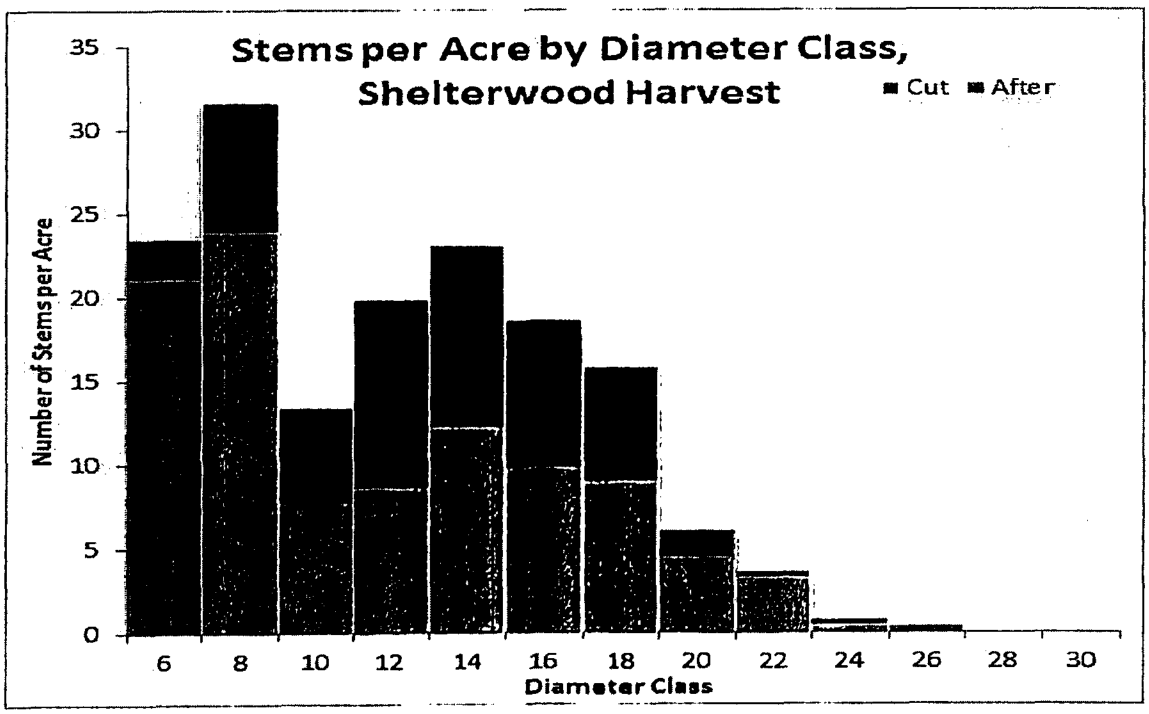

Figure 5. Stems per Acre by Diameter Class for Shelterwood Harvest

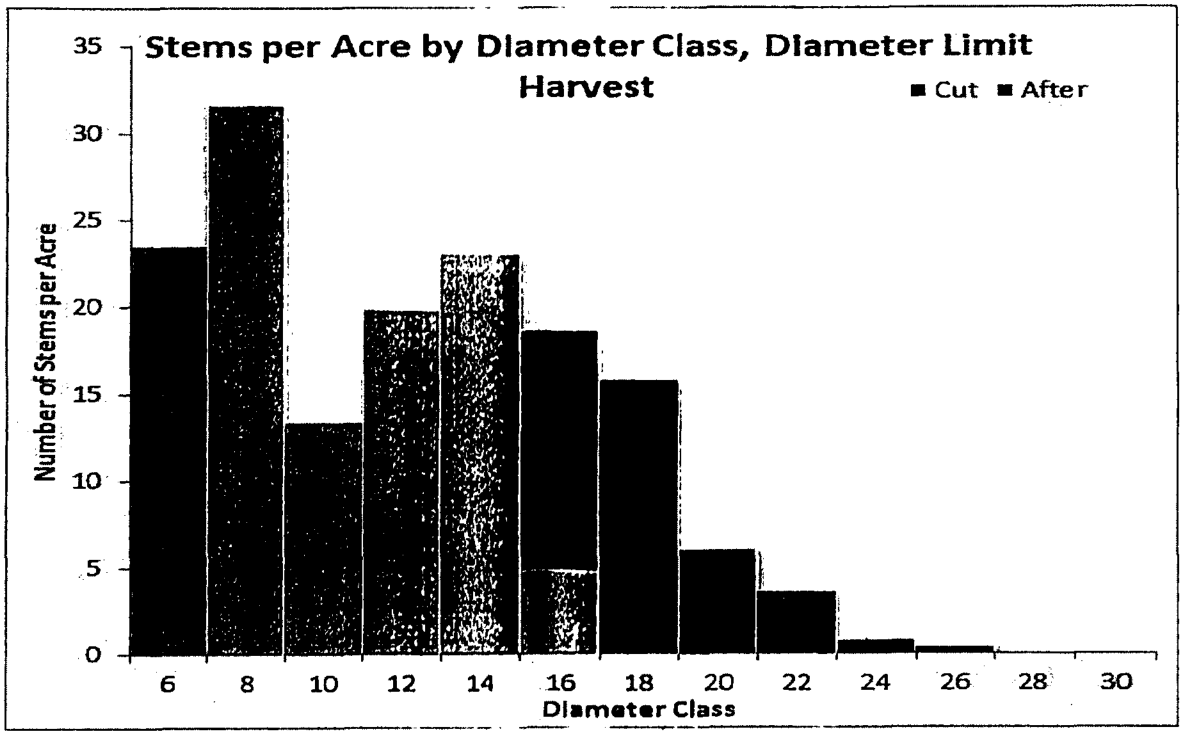

Figure 6. Stems per Acre by Diameter Class for Diameter Limit Harvest

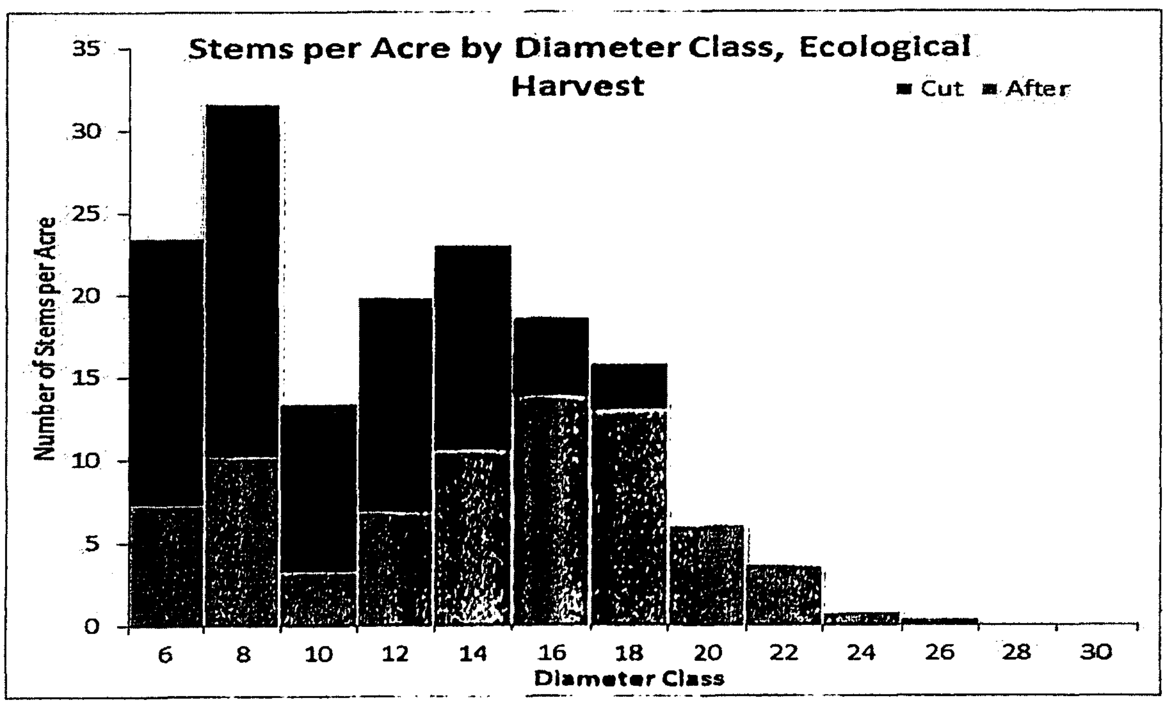

Figure 7. Stems per Acre by Diameter Class for Ecological Harvest

Table 5: Comparison of Species Diversity in Case Studies. Percents represent remaining or removed species composition.

Species Diversity		Crown Thinning		Shelterwood		Diameter Limit		Ecological	
Species	Initial	Cut	After	Cut	After	Cut	After	Cut	After
Black Ash	0.5%	0.0%	0.6%	0.0%	0.8%	0.0%	0.7%	0.0%	1.1%
Black Birch	2.3%	1.8%	2.4%	0.7%	3.2%	0.0%	3.1%	3.5%	1.1%
Beech	4.9%	0.0%	5.7%	1.4%	6.9%	0.0%	6.6%	8.0%	1.6%
Bigtooth Aspen	3.1%	3.6%	3.0%	1.4%	4.0%	0.0%	4.2%	1.5%	4.8%
Basswood	2.1%	0.0%	2.4%	0.0%	3.2%	0.0%	2.8%	2.0%	2.1%
Hemlock	9.0%	0.0%	10.6%	10.1%	8.5%	1.0%	11.8%	0.0%	18.7%
Red Maple	14.0%	0.0%	16.3%	7.9%	17.3%	0.0%	18.8%	26.0%	1.1%
Red Oak	52.5%	94.6%	45.3%	73.4%	40.7%	98.0%	36.6%	47.0%	58.3%
Shagbark Hickory	1.3%	0.0%	1.5%	0.0%	2.0%	0.0%	1.7%	1.0%	1.6%
Sugar Maple	5.9%	0.0%	6.9%	3.6%	7.3%	0.0%	8.0%	7.5%	4.3%
White Ash	3.6%	0.0%	4.2%	0.7%	5.2%	1.0%	4.5%	3.5%	3.7%
White Pine	0.5%	0.0%	0.6%	0.7%	0.4%	0.0%	0.7%	0.0%	1.1%

Table 6: Average DBH by Species by Case Study

Average DBH		Crown Thinning		Shelterwood		Diameter Limit		Ecological	
Species	Initial	Cut	After	Cut	After	Cut	After	Cut	After
Black Ash	10.0	0.0	10.0	0.0	10.0	0.0	10.0	0.0	10.0
Black Birch	7.6	10.0	7.3	10.0	7.3	0.0	7.6	7.3	8.6
Beech	7.9	0.0	7.9	9.9	7.7	0.0	7.9	7.9	8.1
Bigtooth Aspen	13.5	13.1	13.5	12.4	13.7	0.0	13.5	13.6	13.4
Basswood	8.4	0.0	8.4	0.0	8.4	0.0	8.4	6.8	10.0
Hemlock	9.2	0.0	9.2	9.6	9.0	15.8	9.0	0.0	9.2
Red Maple	7.4	0.0	7.4	8.0	7.3	0.0	7.4	7.4	8.6
Red Oak	15.4	15.6	15.4	14.6	16.3	18.3	12.8	13.1	17.5
Shagbark Hickory	7.1	0.0	7.1	0.0	7.1	0.0	7.1	6.7	7.3
Sugar Maple	7.0	0.0	7.0	6.8	7.1	0.0	7.0	6.9	7.2
White Ash	9.9	0.0	9.9	9.5	10.0	16.3	9.4	9.1	10.8
White Pine	9.9	0.0	9.9	12.3	7.4	0.0	9.9	0.0	9.9

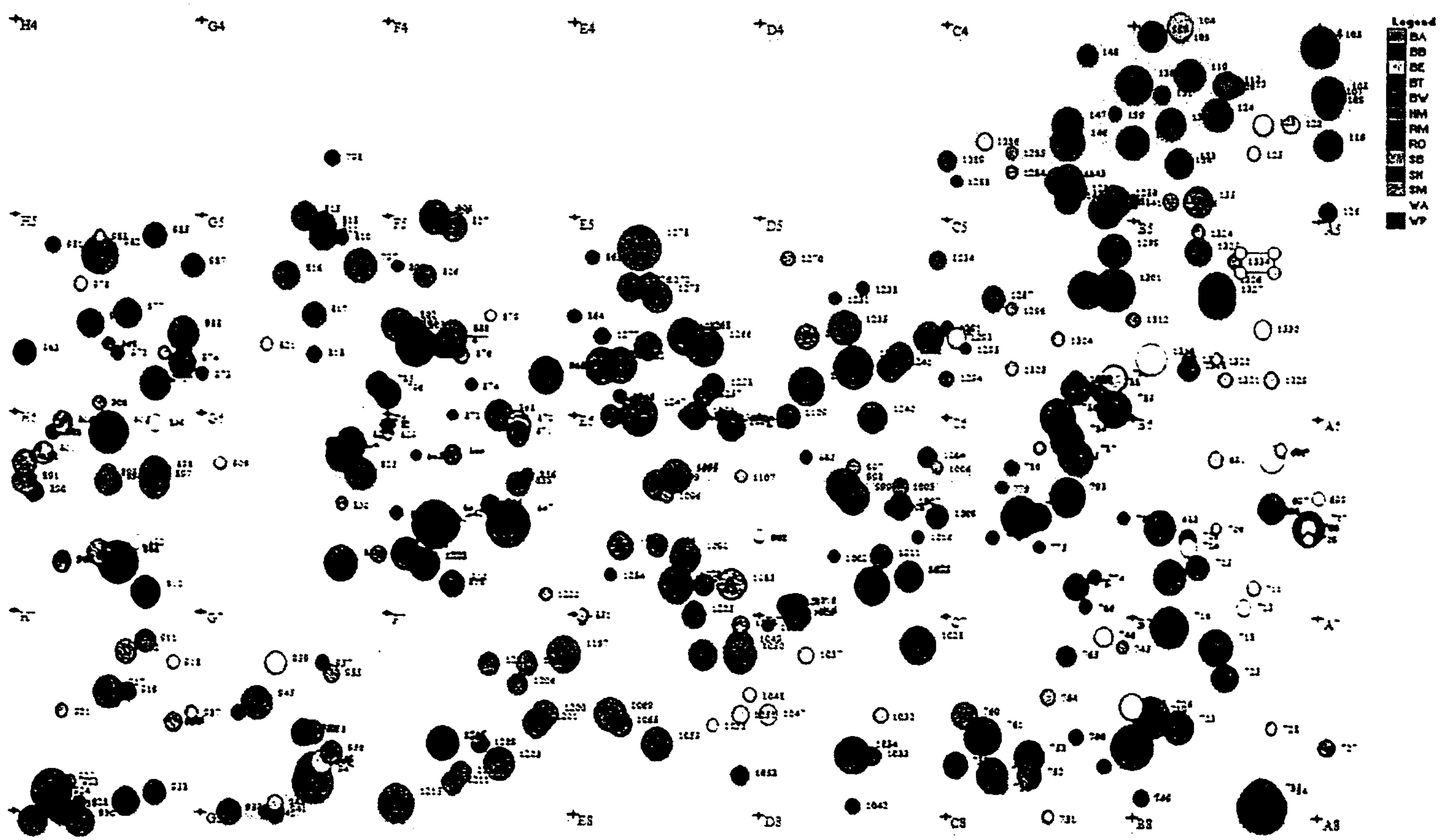

Figure 8: Stem Map of Study Site, Kingman Farm, Madbury, NH

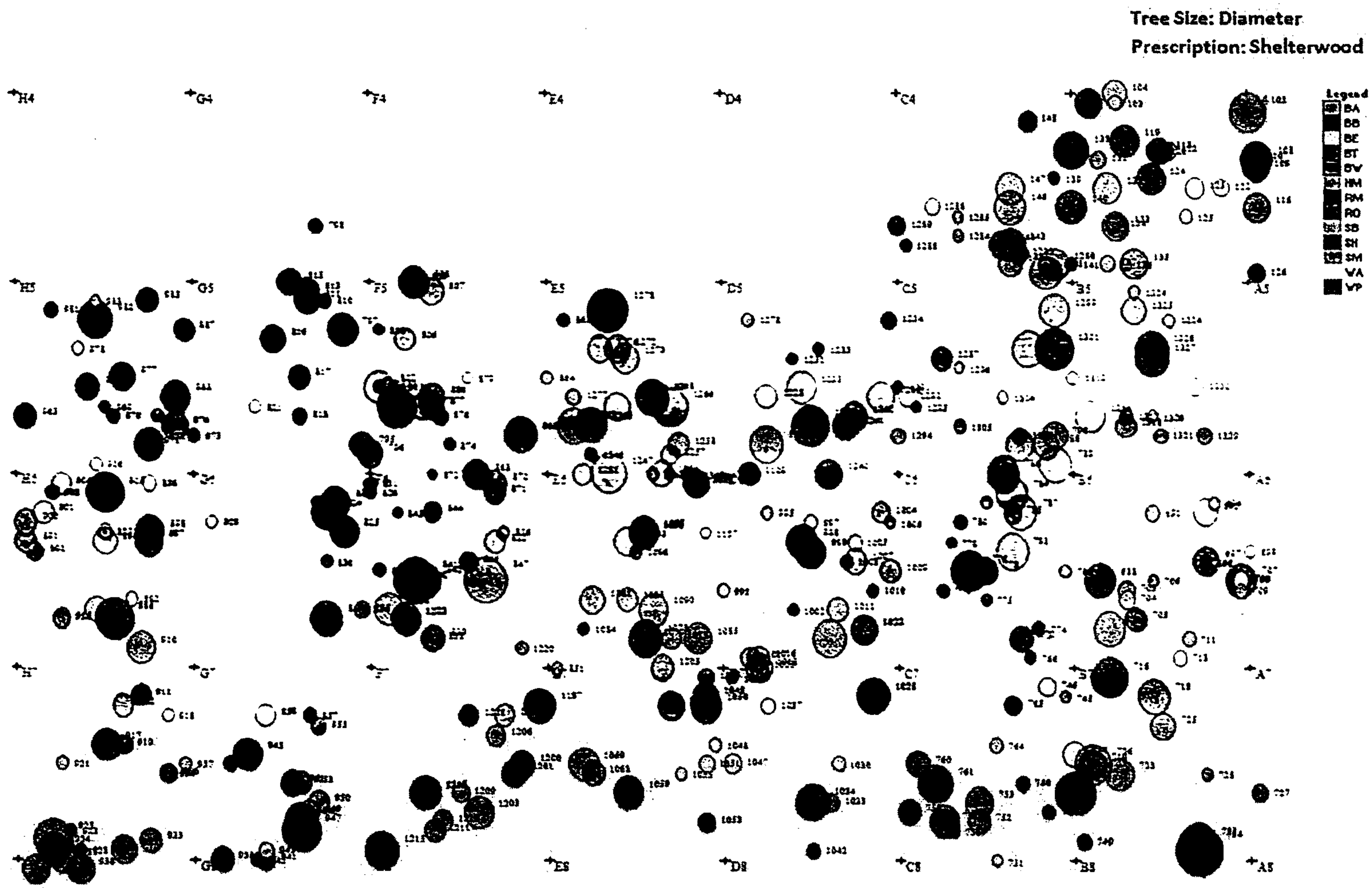

Figure 9: Stem map after Shelterwood Harvest. Pastel colored circles represent harvested trees.

Discussion:

Crown Thinning Harvest:

The crown thinning harvest removed trees that had large crowns thereby creating openings into which the crowns of crop trees could expand (Figure 12, Appendix A). The simulated crown thinning did not sacrifice ecological values; average individual tree ecological score went from 3.45 (out of a possible 12) to 3.31. The average economic score also went down slightly, $32.65 to $27.99 per tree, demonstrating that for this harvest there was no clear trade-off between economic and ecological values. Since this treatment focused on promoting future growth of crop trees in the stand and our model does not project forward, we can only speculate about future outcomes. Because the trees that were removed were co-dominant in the canopy, the remaining co-dominant trees will have room to expand their crowns. This will likely increase the financial value of the crop trees by increasing their growth, thereby increasing their diameter and volume. This will also likely increase the ecological scores of the trees because larger crowns provide more opportunities for nest sites and increase acorn yield (Rose et al., 2012). The Shannon-Wiener Index went up slightly after the harvest because the majority of the trees harvested were oaks and their removal increased the species evenness of the stand (Table 5, Table 6).

Shelterwood Harvest:

The Shelterwood Harvest removed 40% of the basal area and volume while increasing both the average ecological value and the Shannon-Wiener Index slightly from 3.45 and

1.67 to 3.50 and 1.92, respectively. The average economic value went down slightly, \$32.65 to \$29.33 per tree, but that is to be expected when large diameter trees are removed to allow light to the understory. The majority of the trees removed were red oaks because they were the most dominant in the stand but also generally the bigger trees. Post-harvest, Red oak continued to dominate the stand, accounting for 41% of stems with an average DBH of rising from 15.4 inches before harvest to 16.3 inches after harvest (Table 5, Table 6). This dominance of oaks will likely help repopulate the stand with valuable trees. Similarly to the crown thinning treatment, the residual oaks will likely have increased growth in the future which will increase the economic and ecological values. These results support Niese and Strong (1992) findings that shelterwood harvests are beneficial for both future economic and ecological values.

Diameter Limit Harvest:

The Diameter Limit Harvest supports the theory that diameter limit cuttings remove most, if not all, of the valuable trees and leave poor quality timber behind (Fajvan et al., 2002; Kenefic et al., 2005; Nyland, 2005). The average per tree economic value dropped from \$32.65 to \$12.69, while the average ecological score dropped the most of any harvest from 3.45 to 2.86. The short-term financial gain from this harvest greatly reduces the average ecological score for the stand, while the long-term outlook for the stand has a greatly reduced average economic value and average ecological score. The biodiversity index for the stand rose the most of any stand from 1.67 to 1.92. This rise in biodiversity can be attributed to the fact that 98% of the trees removed in this harvest were red oaks, lowering the red oak population in the stand from 52.5% to 36.6% (Table 5). This change in species composition improved the species richness for the stand, thereby increasing the SWI.

Ecological Harvest:

The ecological harvest was designed to improve the average ecological score for the stand, and while the raw data indicates that the goal was accomplished, further evaluation might suggest otherwise. The average ecological score rose from 3.45 to 4.53, but most of the trees removed were small diameter (10 inches) and in the understory (Table 6). This will not promote a healthy and diverse future forest. This type of harvest is not necessarily feasible in a practical sense because it requires evaluating every tree for all ecological scores and then selecting the lowest scoring trees. Even after finding all the lowest scoring trees, removing only those trees would be very labor intensive and costly because the majority of the trees are small diameter trees with little or no economic value. Those issues aside, this harvest was helpful in demonstrating the effects of a harvest that focused on promoting trees with high ecological scores.

Biodiversity versus Ecological Score

Biodiversity is often used as a sole indicator of the ecological value of a stand (Niese and Strong, 1992) but our data confirms that tree biodiversity is only one aspect of the ecological value of a stand. This supports Bullock et al. (2011) and Costanza et al. (2007) findings that there might not be a relationship between biodiversity and ecological values. In the Diameter Limit Harvest, the majority of the trees harvested were red oaks and because red oaks were the most dominant species, their removal increased the species evenness of the stand, thereby increasing the biodiversity score (Table 5). However, the average ecological score dropped after this harvest. One possible explanation for the decline in average ecological score is that in this stand red oaks generally have a higher ecological score. This is because red oaks are one of two species that qualify for the hard mast producer ecological score and because the majority of the large dominate trees in the stand are red oaks.

In the Ecological Harvest, the average ecological score rose while the biodiversity index fell. These changes are caused by a potential limitation in the system that assigns lower scores to small diameter trees because they currently lack high ecological values. The current stand stratification is an overstory of mainly red oak with an understory of mixed hardwoods. These understory hardwoods are the low ecological scoring trees that are being removed. Their removal greatly diminishes the species evenness of the stand. The Crown Thinning and Shelterwood Harvests both had increased biodiversity but only slight changes in average ecological value. As previously noted, these increases in biodiversity are from the removal of the majority species, red oak. The differences in biodiversity and ecological values across the four harvests suggest that species biodiversity and ecological values are not related.

Economic and Ecological Trade-offs

The results of the case study harvests suggest that there are no trade-offs between economic and ecological values. Both the crown thinning and shelterwood harvest had slight changes in average economic and ecological values; there was no clear trade-off between economic or ecological values (Figure 11). The diameter limit harvest was designed as a short-term monetary gain harvest which could conceivably be a landowner's objective; however, the effects of the harvest on the residual economic and ecological values were so dramatic that it would not be a wise decision for a landowner. Both the economic and ecological values of the stand dropped to the lowest observed levels after the harvest. This suggests that even though a large immediate economic gain was created from the harvest, the long term economic value of the stand was diminished and will likely negate any trade-offs between the economic value and the now lowered ecological scores. The ecological harvest was intended to replicate a landowner's goal of improving the ecological value of their stand. This harvest strengthened the notion that there are no trade-offs between economic and ecological values. Removing the lowest ecologically scoring trees improved both the average economic and ecological scores of the stand. Figure 10 shows the relationship between economic and ecologic values for every tree in the stand. A trend appears to exist but only for red oak. This trend can be explained by a bias in the scoring system. Figure 11 shows the relationship between economic and ecologic values for all species except red oak. By removing red oak from the graph, the presence of a relationship is absent from the graph. Within the framework of our ecological scoring system, there does not appear to be any present trade-offs between economic and ecological values, therefore, landowners can focus more on the overall effects of the harvest they choose.

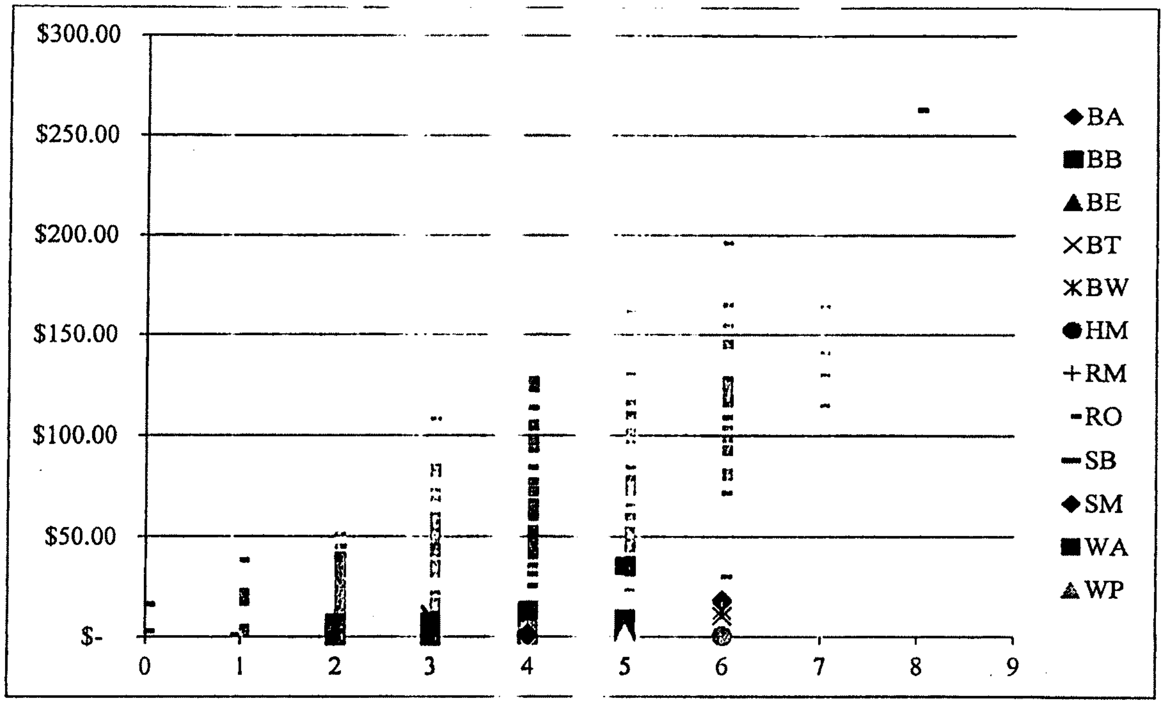

Figure 10: Economic versus ecologic values by tree species

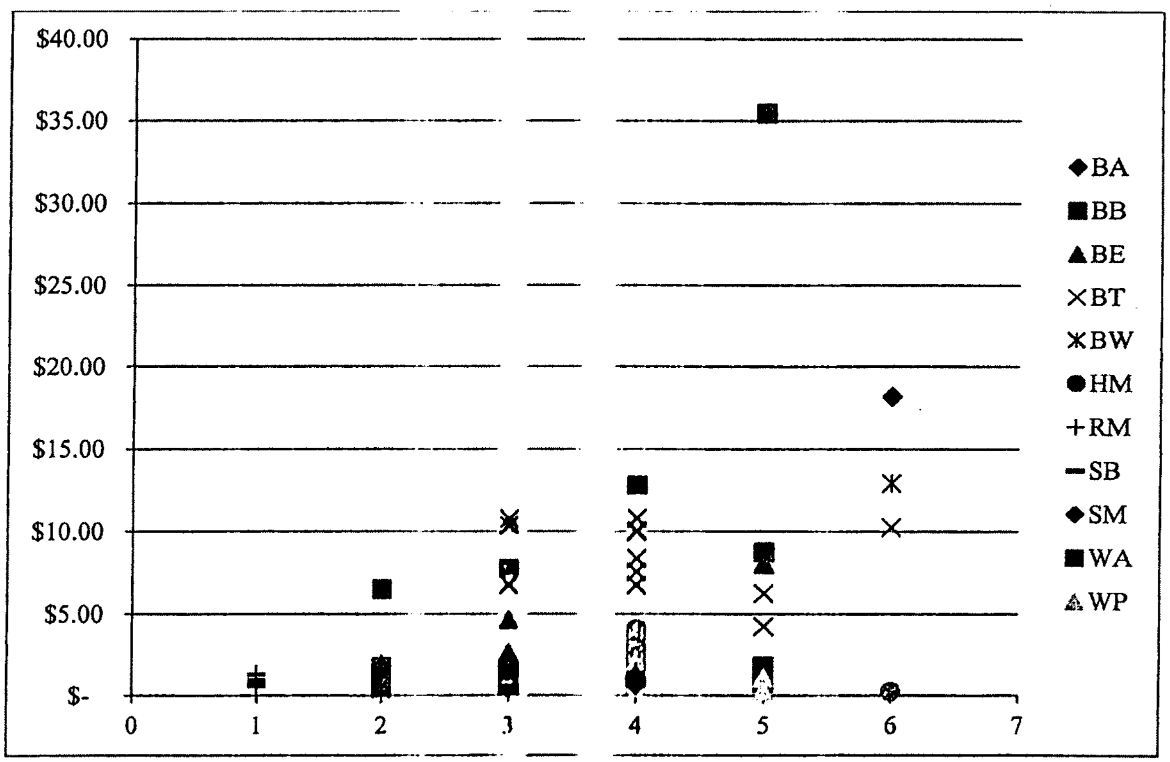

Figure 11: Economic versus ecologic values by tree species without red oak

Potential Faults and Solutions

This study is one of the first of its kind and therefore there are many areas that could be improved. First, the current ecological scoring system favors large diameter oaks. Large oaks receive a high score for food production and generally have large crowns that award them high wildlife scores. Any signs of mortality risks further raise the score for these trees. This imbalance could potentially lead to a pure oak stand having a higher average ecological value than a mixed species stand. This issue could be resolved by adding a weighting system to the ecological scores. The weighting system could be tied to the region or desired outcome of the forest. For instance, if biodiversity was very important to the landowner and production of hard mast was not, the rarity ecological score could be weighted more and the hard mast score could be weighted less. However, McElhinny et al. (2005) did note the difficulties of creating a weighting system for ecological indexes.

Second, there are currently only four ecological scores being used to determine ecological value. As previously mentioned, this can lead to an uneven scoring system with a bias towards specific species. More ecological scores could easily be added but for this study we went with four scores to keep the analysis simple. These additional scores could be region or user based, such as a score for specific habitat characteristics for endangered species or a score for trees with a certain type of lichen on them. Another option would be to add a "special" tree category that would allow users to designate a tree as ecologically important for a reason not associated with an existing ecological score. This would create a more thorough ecological valuation but would increase the data collection time. The score could also be simplified to decrease data collection time and make the evaluations more practical.

Third, small diameter trees are misrepresented as having a low ecological score. For example, a 6 inch DBH red oak tree would have an ecological score of 0 out of 12. This is because the tree does not offer any shelter for wildlife, is too small to produce hard mast, has a very low risk of mortality and is very common in the stand. The scoring system does not, however, take into consideration the potential of the tree. The tree may have a low ecological score now but it does have the potential to contribute ecologically to the stand. One possible way to account for potential values would be to use a tree grading system that evaluates a tree of any size for its current value or potential value. The French ABCD grading method already accounts for smaller trees in this manner so converting to their system for future work would not be difficult. Assessing the potential value of smaller trees would also be useful when analyzing the economic value of the stand.

Fourth, the current ecological scores might not be easily applied to another forest type or another harvesting method. These ecological scores were developed for a partial removal harvests in a pine-oak stand. Applying the same scoring system to a maple, beech and birch stand might have different results. Someone wanting to replicate these methods elsewhere would need to reevaluate the ecological scores to reflect a different ownership, forest type and management approach.

Fifth, the current model only considers the present economic and ecological values. Applying a growth and yield model would allow users to project the results of their harvests. Growth and yield programs, such as the US Forest Service's Forest Vegetation Simulator or Northeast Decision Model, could easily be adapted to work with this model's data.

Conclusions:

This study shows that different harvest types can have different effects on the ecological values of a forested stand. The Diameter Limit Harvest supported the well-established notion that diameter limit harvests are most always a poor choice for anything other than a short-term financial gain objective. The Shelterwood and Crown Thinning Harvests improved species evenness while leaving average ecological scores relatively unchanged and promoting future growth in the stand. The Ecological Harvest improved the average ecological score of the stand at the cost of the species evenness and future growth. Economic and ecological values appeared to be related and showed no trade-offs between the two. This allows landowners to focus more on the type of harvest and the overall outcomes of the harvest than the relationship between economic and ecological values. We also showed potential benefits and faults of four common harvests to aid in landowner decisions.

Tree biodiversity and ecological values were shown to be unrelated. Determining which measurement is best for evaluating the non-monetary objective for the forest depends on the long term goals of the landowner. Improving species richness may rely on a biodiversity index while monitoring mortality risk may rely on ecological scores.

While this study does have its faults and limitations, the methodology can be used as a guide for establishing permanent plots to monitor ecological and economic values. These ecological value categories can also be used as a rapid ecological assessment to quickly identify ecological characteristics in trees. This rapid ecological assessment can be used to aid foresters and landowners in their decision making.

References

Bruciamacchie M. Le marteloscope, un outil pour ap-prendre la gestion durable. Exemple d'évaluation de différents scénarios au marteloscope de Zittersheim (Vosges du Nord). (2005):237–248.

Bruciamacchie M, Pierrat J-C, Tomasini J. Modèles explicatif et marginal de la stratégie de martelage d'une parcelle irrégulière. Annals of forest science (2005) 62:727-736.

Bullock JM, Aronson J, Newton AC, Pywell RF, Rey-Benayas JM. Restoration of ecosystem services and biodiversity: conflicts and opportunities. Trends Ecol. Evol. (2011) 26:541-549.

Buongiorno J, Dahir S, Lu H-C, Lin C-R. Tree size diversity and economic returns in uneven-aged forest stands. For. Sci. (1994) 40:83-103.

Buongiorno J, Kolbe A, Vasievich M. Economic and ecological effects of diameter-limit and BDq management regimes: Simulation results for northern hardwoods. Silva. Fenn. (2000) 34:223-235.

Butler BJ. Family forest owners of the United States, 2006. Gen. Tech. Rep. NRS-27. Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station (2008) 73.

Butler BJ, Leatherberry EC. Americas family forest owners. Journal of Forestry (2004) 102:4-14.

Costanza R, Fisher B, Mulder K, Liu S, Christopher T. Biodiversity and ecosystem services: A multi-scale empirical study of the relationship between species richness and net primary production. Ecological economics (2007) 61:478-491.

DeGraaf RM, Healy WM. New England wildlife: management of forested habitats. (1992): US Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.

DeGraaf RM, Yamasaki M. New England wildlife: habitat, natural history, and distribution. (2001): UPNE.

Fajvan MA, Knipling KE, Tift BD. Damage to Appalachian hardwoods from diameter-limit harvesting and shelterwood establishment cutting. North. J. Appl. For. (2002) 19:80-87.

Fortin M, Bédard S, DeBlois J, Meunier S. Predicting individual tree mortality in northern hardwood stands under uneven-aged management in southern Québec, Canada. Annals of forest science (2008) 65:205-205.

Franks EC, Reeves JW. A formula for assessing the ecological value of trees. Journal of arboriculture (1988) 14.

Guillemette F, Bedard S, Fortin M. Evaluation of a tree classification system in relation to mortality risk in Quebec northern hardwoods. For. Chron. (2008) 84:886-899.

Hanks LF. Hardwood tree grades for factory lumber. US Northeastern Forest Experiment Station. USDA Forest Service Research Paper NE (1976).

Honer T. Standard volume tables and merchantable conversion factors for the commercial tree species of central and eastern Canada. (1967): Department of Forestry and Rural Development.

Kenefic LS, Sendak PE, Brissette JC. Comparison of fixed diameter-limit and selection cutting in northern conifers. North. J. Appl. For. (2005) 22:77-84.
Leak WB, Sendak PE. Changes in species, grade, and structure over 48 years in a managed New England northern hardwood stand. North. J. Appl. For. (2002) 19:25-28.
Loftis DL. A SHELTERWOOD METHOD FOR REGENERATING RED OAK IN THE SOUTHERN APPALACHIANS. For. Sci. (1990) 36:917-929.
Lu H-c, Buongiorno J. Long-and short-term effects of alternative cutting regimes on economic returns and ecological diversity in mixed-species forests. For. Ecol. Manage. (1993) 58:173-192.
Martin AC, Zim HS, Nelson AL. American wildlife and plants. (1961): Courier Dover Publications.
McElhinny C, Gibbons P, Brack C, Bauhus J. Forest and woodland stand structural complexity: Its definition and measurement. For. Ecol. Manage. (2005) 218:1-24.
Niese JN, Strong TF. Economic and tree diversity trade-offs in managed northern hardwoods. Canadian Journal of Forest Research (1992) 22:1807-1813.
Nyland RD. Diameter-limit cutting and silviculture: a comparison of long-term yields and values for uneven-aged sugar maple stands. North. J. Appl. For. (2005) 22:111-116.
Pielou E. The measurement of diversity in different types of biological collections. Journal of theoretical biology (1966) 13:131-144.
Rast ED, Sonderman DL, Gammon GL. A guide to hardwood log grading. (1973): Forest Service, US Department of Agriculture, Northeastern Forest Experiment Station.
Reay RS. Management of Eastern Hemlock for Deer Wintering Areas. In: Symposium on Sustainable Management of Hemlock Ecosystems in Eastern North America (2000).
Rose AK, Greenberg CH, Fearer TM. Acorn production prediction models for five common oak species of the eastern United States. The Journal of Wildlife Management (2012) 76:750-758.
Schemnitz SD. Wildlife management techniques manual. (1980): Wildlife Society.
Schuler TM. Fifty years of partial harvesting in a mixed mesophytic forest: composition and productivity. Canadian Journal of Forest Research (2004) 34:985-997.
Shannon CE. A MATHEMATICAL THEORY OF COMMUNICATION. Bell System Technical Journal (1948) 27:379-423.
Sinacore K. Understanding the economic and ecological outcomes of selection silviculture on a northern hardwood forest (2013) Durham, NH: University of New Hampshire. 84.
Smith DM, Larson BC, Kelty MJ, Ashton PMS. The practice of silviculture: applied forest ecology. (1997): John Wiley and Sons, Inc.
Soucy M, Cyr A, Lussier J. Gounamitz I Marteloscope (2013). Université de Moncton.
Welsh CJ, Healy WM. Effect of even-aged timber management on bird species diversity and composition in northern hardwoods of New Hampshire. Wildlife Society Bulletin (1993):143-154.
Whitman AA, Hagan JM. An index to identify late-successional forest in temperate and boreal zones. For. Ecol. Manage. (2007) 246:144-154.

Wiant Jr HV, Castaneda F. Mesavage and Girard's volume tables formulated. Resource Inventory Notes BLM (1977) 4.

Appendix A: Post-Harvest Stem Maps

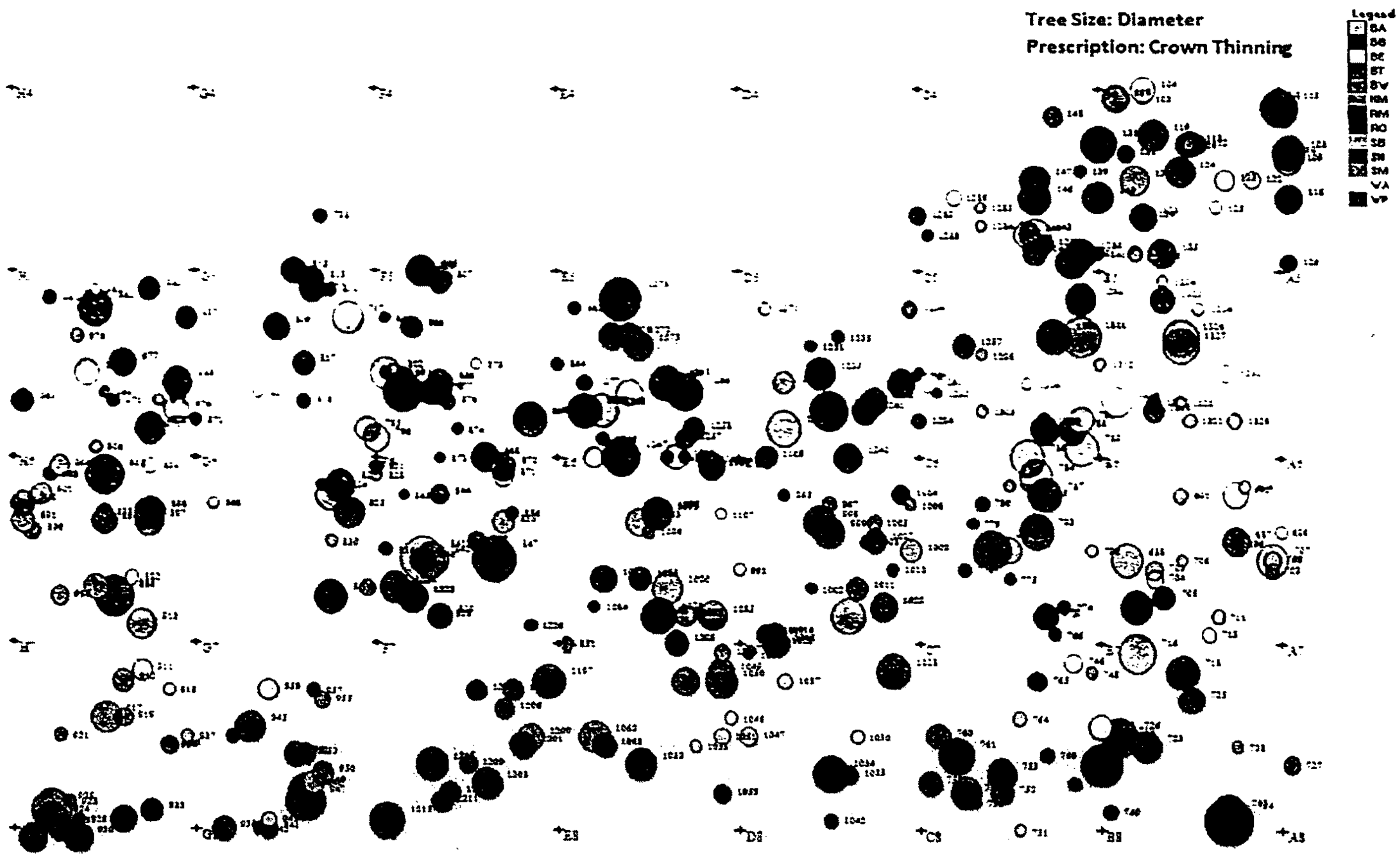

Figure 12: Stem Map After Crown Thinning Harvest. Pastel colored circles represent harvested trees.

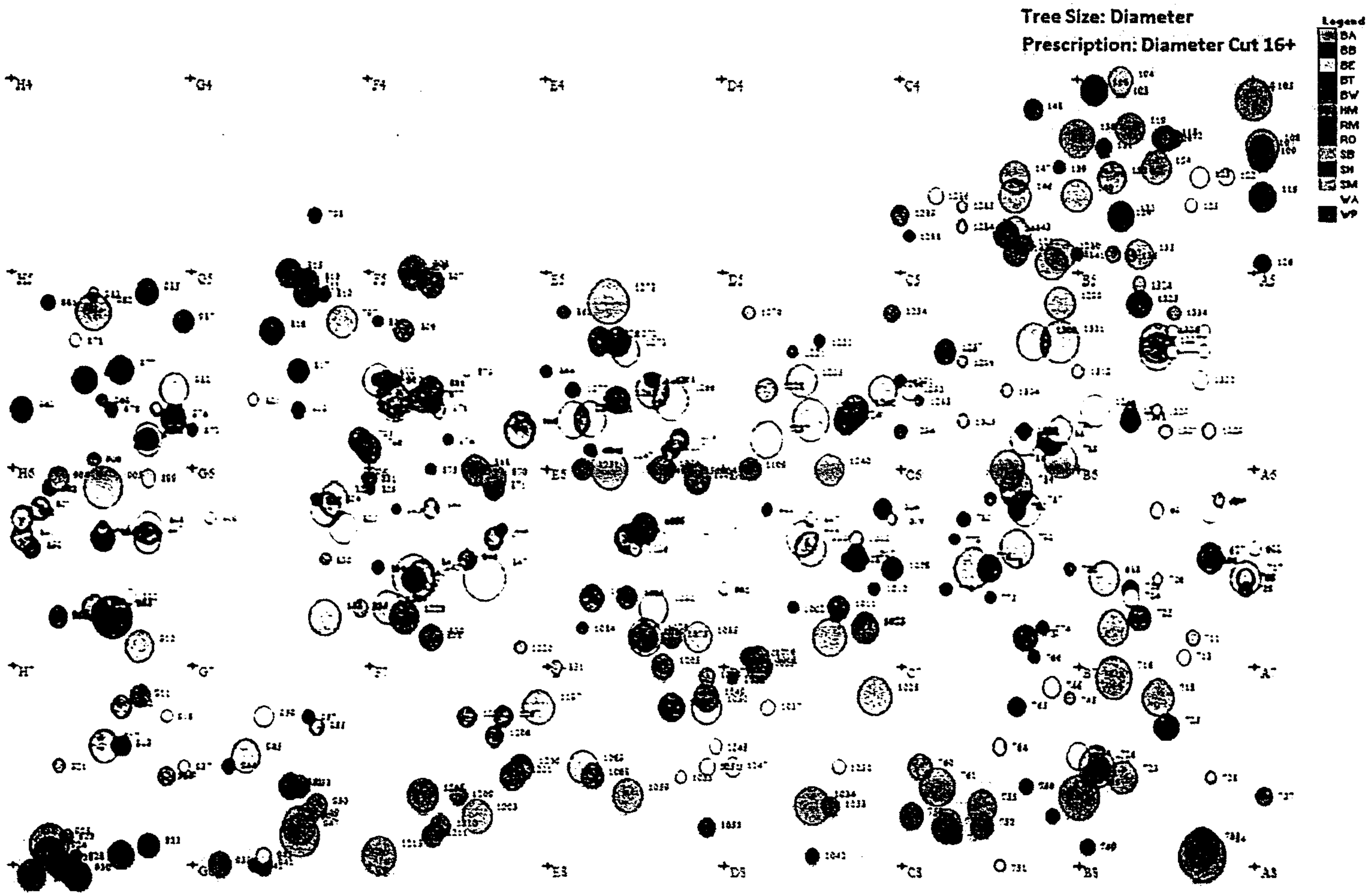

Figure 13: Stem Map After Diameter Limit Harvest. Pastel colored circles represent harvested trees.

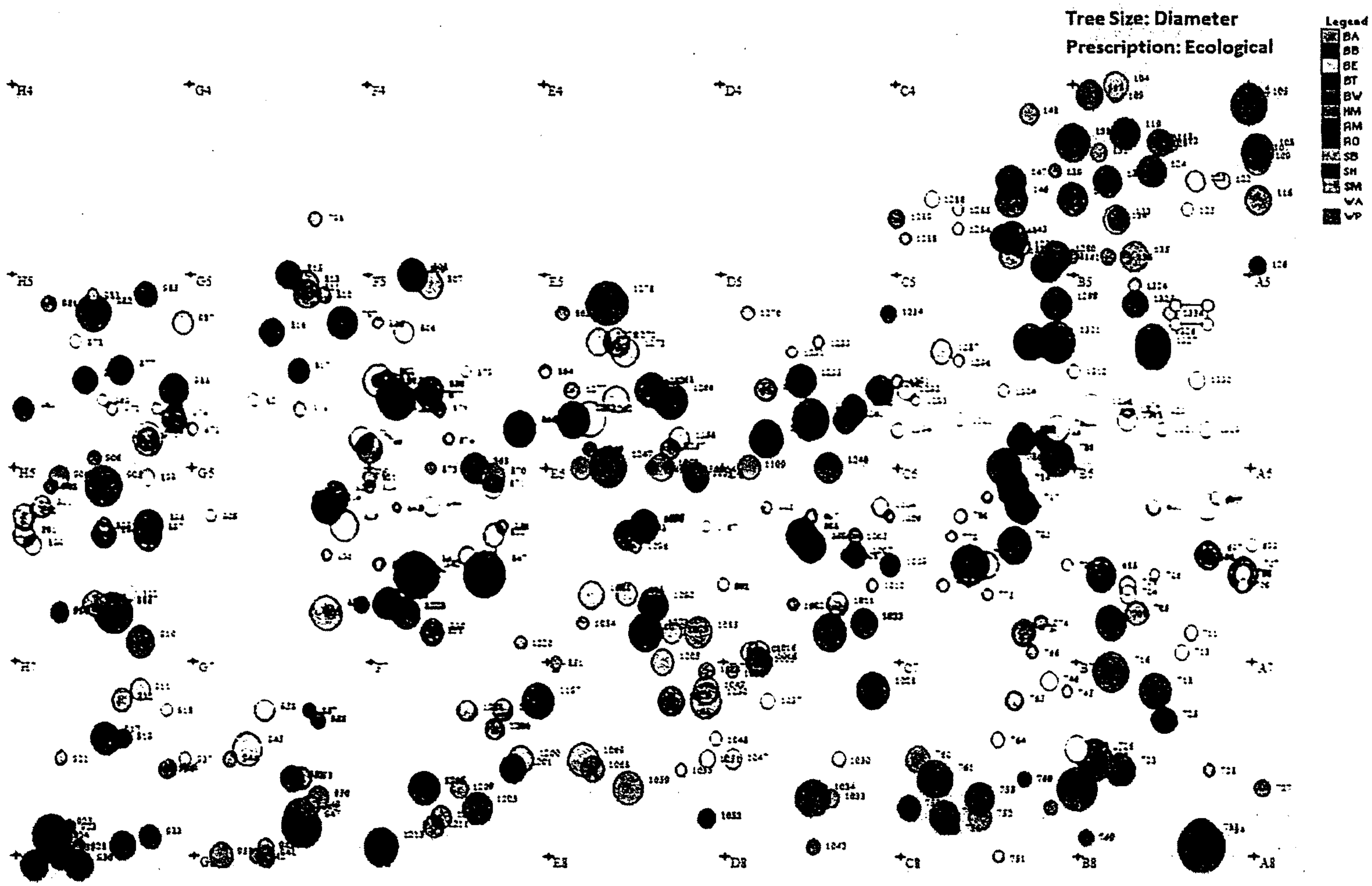

Figure 14: Stem Map After Ecological Harvest. Pastel colored circles represent harvested trees.

Appendix B: Species Coefficients for Honer's Volume Equation

Table 7: Species Coefficients for Honer's Volume Equation

Species	Honer's (1967) coefficients		Taper	metric derived coefficients		
	b_1	b_2	Coefficient	a_0	a_1	a_2
White Pine	0.691	363.676	0.184	0.691	110.848	0.004319
Red Pine	0.710	355.623	0.151	0.710	108.394	0.004331
Jack Pine	0.897	348.530	0.151	0.897	106.232	0.004331
Black Spruce	1.588	333.364	0.164	1.588	101.609	0.004327
Red Spruce	1.226	315.832	0.169	1.226	96.266	0.004325
White Spruce	1.440	342.175	0.176	1.440	104.295	0.004322
Balsam Fir	2.139	301.634	0.152	2.139	91.938	0.004331
Cedar	4.167	244.906	0.155	4.167	74.647	0.004330
Hemlock	1.112	350.092	0.155	1.112	106.708	0.004330
Trembling Aspen	-0.312	436.683	0.127	-0.312	133.101	0.004341
Balsam Poplar	0.420	394.644	0.127	0.420	120.287	0.004341
White Birch	2.222	300.373	0.176	2.222	91.554	0.004322
Yellow Birch	1.449	344.754	0.181	1.449	105.081	0.004320
Maple	1.046	383.972	0.145	1.046	117.035	0.004334
Basswood	0.948	401.456	0.145	0.948	122.364	0.004334
Beech	0.959	334.829	0.145	0.959	102.056	0.004334
Black Cherry	0.033	393.336	0.145	0.033	119.889	0.004334
White Elm	0.634	440.496	0.145	0.634	134.263	0.004334
Ironwood	1.877	332.585	0.145	1.877	101.372	0.004334
Red Oak	1.512	336.509	0.145	1.512	102.568	0.004334